

# Are soft-sediment trace fossils (ichnofossils) a time problem for the Flood?

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Rapidly-burrowing organisms are capable of disturbing sediment in seconds to minutes, while intense bioturbation can take less than a day for a 12-cm bed. A number of mechanisms allow for the simultaneous bioturbation of multiple horizons of sediment, including slurry flows with their internal buoyancy. A new hypothetical mechanism is defined positing that zones of rapid lithification alternated with Flood deposition, thus temporarily protecting deeply-buried organisms from the immobilizing effects of thick sediment overburden. This allowed for the simultaneous bioturbation of considerable thicknesses of Flood sediment soon after its deposition.

Traces of organisms' burrowing movements in the once-soft sediment are most commonly manifested as disturbances of laminae in sedimentary rocks (figure 1). They also occur as discrete individual trace fossils.<sup>1</sup> Many pictures of ichnofossils (individual trace fossils) are available online.<sup>2</sup> Figures 2 and 3 provide examples collected by the author. Owing to the ubiquity of ichnofossils throughout Phanerozoic sedimentary rock, combined with the inferred spans of time necessary for the construction of each burrowed layer or individual ichnofossil (supposedly at one stratigraphic horizon at a time), trace fossils have sometimes been perceived as an insurmountable challenge to Flood geology. Although ichnofossils have been considered in detail in previous creationist geologic studies,<sup>3,4</sup> they have never been systematically analyzed in the light of the creationist-diluvialist paradigm.

As in all my previous works, I support the Noachian Deluge for the origin of the bulk of the earth's Phanerozoic sedimentary rocks, and use standard uniformitarian terms only for purpose of reference. This work focuses on:

1. Inorganic and body fossil alternatives to supposed ichnofossils,
2. Biological candidates for the very rapid construction of ichnofossils during (and after) the deposition of Flood sediment,
3. Overcoming rapid sedimentation as a limiting factor in the construction of ichnofossils, and
4. The proposal and development of a new hypothetical mechanism, Penecontemporaneous Partially Lithified Crusts (PPLCs), that reduces the time required for the construction of trace fossils that occur in direct superposition.

To complement this study of soft-sediment ichnofossils, an ensuing paper<sup>5</sup> will consider both body fossils and ichnofossils of inferred hard-substrate dwellers, thereby extending earlier field work<sup>6</sup> on hardgrounds.

## Trace fossils or inorganic sedimentary features?

Physical features can be mistaken for ichnofossils, although numerous uniformitarian investigators have addressed the distinctiveness of biogenic features, notably Boyd<sup>7</sup> and Eckdale *et al.*<sup>8</sup> In contrast to abiogenic traces, biogenic ones are considered to have relatively uniform dimensions. The biogenic origin of certain traces is proven by the presence of features that only a living organism can produce, such as burrow lining or spreite structures (figure 3). However, these highly-diagnostic features are very uncommon. In most cases, the distinction between biogenic and abiogenic traces is not so clear-cut:

'Many a spirited argument has arisen on the outcrop between geologists who take opposing views on the biogenic vs non-biogenic origin of a particular structure in the rock, and a good share of these arguments go unresolved because of either poor preservation of the structure or lack of clear criteria for distinction between alternative solutions.'<sup>9</sup>

'Nevertheless, even given ideal conditions of preservation, it may still be difficult to separate the two genetically disparate categories and even experienced ichnologists may be perplexed, particularly when working with material in drill cores. Thus, the distinction of pseudofossils from trace fossils is not always a straightforward task, and commonly relies on detailed analysis with an experienced eye.'<sup>10</sup>

It is sometimes claimed that the *in situ* status of trace fossils is demonstrated by their lack of preferred orientation. After all, preferred orientation is characteristic of transported objects. However, there are instances where the current orientation of suites of trace fossils, representing different ichnogenera, have been determined, and found to be decidedly nonrandom.<sup>11</sup> Random orientation is not proof for absence of transport, as indisputably-transported objects need not show any preferred orientation.<sup>12</sup>

Collapse structures in sediment can be distinguished from biogenic escape structures by virtue of the fact that only the laminae in escape structures have a constant dip throughout the vertical extent of the structure.<sup>13</sup> This conclusion is supported by a series of experiments,<sup>14</sup> which also indicate that collapse structures tend to have a recognizably wide V-pattern in the sediment. However, these experiments were limited to loose sand, and tell us nothing about the morphologies of collapse structures in compacted sand, let alone more argillaceous or carbonate material, which is more typical of sedimentary rock in general.

The trace fossil *Thalassinoides* is a very common one, notably in Cretaceous rocks. Though currently attributed to burrowing, it had, until recent times, enjoyed numerous and diverse interpretations that ranged from inorganic to body-fossil origins.<sup>15</sup> Although non-burrowing origins have fallen out of favour, they should be reconsidered on a case-by-case basis.

Some geologists believe (at least tacitly) that, when in doubt, one should assume a biological origin, as shown by the following example:

‘In the original investigation of *Arumberia* the biogenic interpretation was favoured because the authors were unaware of any physical mechanism that could explain the radial arrangement of grooves and ridges that characterize the structure.’<sup>16</sup>

To the extent that a biogenic explanation is the default one for a structure, this creates a bias that hinders the discovery of physical origins of ‘trace fossils’. Furthermore, arguments for biogenicity based on the self-consistency of structures are of questionable validity once removed from an actualistic context. Consider gas-escape structures. As noted previously,<sup>17</sup> the escape of gas or water through sediment can account for disturbed laminae (as shown in figure 1). Gas escape structures, unlike burrows, usually display widely different diameters and vertical extents in the sediment.<sup>18</sup> Such reasoning has plausible validity whenever the gas is of localized origin, as typically occurs in a modern sedimentary environment. However, if massive amounts of gas were simultaneously released in the sediment, and large areas and volumes of sediments were under fairly uniform conditions of overpressure during the Flood, a greater degree of self-consistency in the geometries of gas-escape conduits in the sediment could be expected over that seen in modern environments. Only suitable experiments can probe the

upper limits of self-consistency in the geometry of gas escape structures that originate under unusual conditions but none have, to my knowledge, ever performed.

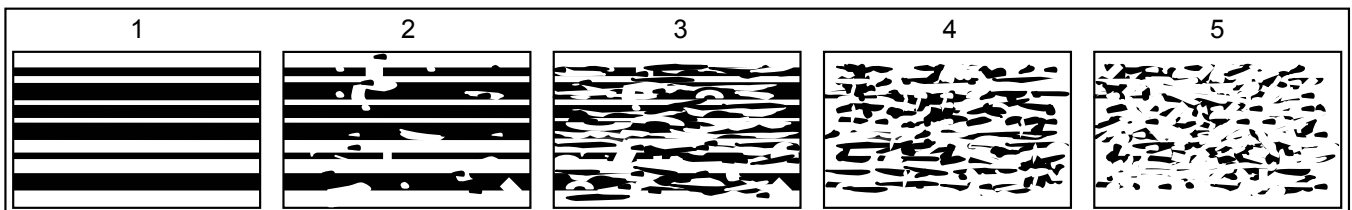
Pseudoburrows originating from plant roots or rotting vegetation can closely resemble genuine subaqueous burrows,<sup>19</sup> and it is recognized that attempts to distinguish them can lead to circular reasoning.<sup>20</sup> Furthermore, in a Flood context, one must factor the existence of colossal amounts of uprooted plants and rotting vegetation during the deposition of sedimentary rocks in general.

There are many difficulties in identifying ichnofossils with certainty. Many so-called trace fossils cannot be identified taxonomically either because they are poorly preserved or because they are not seen in three dimensions in outcrop or core.<sup>21</sup> Sedimentary laminae are commonly punctuated by mottling that is not ichnotaxonomically identifiable.<sup>22</sup> While criteria exist for distinguishing biogenic and abiogenic traces, the reliability of these criteria is unproven. It would be helpful if some kind of ‘Certainty Index’ was developed to rate the inferred degree of certainty of the biotic origins of a given structure, which could then be applied systematically to sedimentary strata in general.<sup>23</sup>

### Trace fossils or body fossils?

The argument that trace fossils are necessarily made by the movements of organisms is weakened by the fact that ichnologists can seldom relate specific trace fossils to the work of a single species.<sup>24</sup> Moreover, if structures found in sedimentary rocks are too complex for a plausible physical explanation, it does not necessarily follow that they are ichnofossils. They may instead be body fossils, perhaps exotic ones.

The argument that ichnofossils are too self-consistent in size and geometry to be misdiagnosed body fossils is dubious. Known tracemaking organisms of even the same species are known to vary considerably in size and dimensions and to make correspondingly variable traces. No clear definition of self-consistency of particular trace fossils has been found in the ichnological literature. Moreover, an appreciably diverse group of traces is often pigeonholed into the same ichnogenus. For example, the common ichnofossil *Zoophycos* covers an excessive morphospace of forms, and is in need of revision.<sup>25</sup> The common ichnofossil *Chondrites* (as shown in figure 2), includes individuals having central



**Figure 1.** Ichnofabric indices based on the degree of bioturbation of sedimentary bedding for inferred shelf deposits (also available for other inferred sedimentary environments<sup>107</sup>). **1)** None. **2)** <10%. **3)** 10–40%. **4)** 40–60% (with last vestiges of bedding discernable). **5)** >60% (with bedding no longer recognizable, but sedimentary fabric itself still intact). The final stage of a virtually complete homogenization of this fabric is not shown. (After Drosser and Bottjer<sup>108</sup>).

shafts ranging in diameter from less than 0.5 mm to 20 mm. The lengths of the branchings range from 10 mm to over 500 mm.<sup>26</sup> The diameter of *Scoyenia gracilis* burrows can vary by nearly an order of magnitude (from 1.2 to 10 mm).<sup>27</sup> Specimens of the well-known ichnogenus *Rusophycus* have length/width ratios ranging from 0.63 to 2.08, and vary in length from less than 1 cm to 13 cm.<sup>28,29</sup>

Ironically, most trace fossils were once regarded as body fossils. For instance, *Chondrites* (as shown in figure 2) was interpreted as a fucoid (fossil alga) throughout the 19<sup>th</sup> century<sup>30</sup> and up to as recently as the 1950s.<sup>31,32</sup> This is not solely of historical interest as there are, to this day, various disagreements about the trace-fossil versus plant-fossil origin of certain sedimentary phenomena. This holds for features encountered in the Early Tertiary Point Reyes Conglomerate of California,<sup>33</sup> as well as the ‘pipe organ’ structures in the Carboniferous of Kentucky.<sup>34</sup> The foregoing are far from isolated instances. It is sobering to realize that the entering of ‘problematic fossils’ or ‘problematica’ into the GEOREF database<sup>35</sup> pulls up nearly 3,000 articles, a notable fraction of which touch on this problem.

One dubious argument against a plant origin for structures such as *Chondrites* is the consistent diameter of all branches and the absence of taper within their respective lengths (figure 2). However, this does not exclude a plant origin.<sup>36</sup> Moreover, some putative ichnofossils such as *Zoophycos* include branches that do taper.<sup>37</sup> Finally, all arguments about supposedly diagnostic ichnofossil geometry must face the fact that the extant biosphere is an impoverished remnant of the antediluvian one. Hence, our knowledge of the potential range of geometries of living organisms is necessarily limited. This means that we may never know which so-called trace fossils may actually be the body fossils of unusually-shaped organisms. Considering, for example, the bizarre geometries of some known fossil organisms (e. g., the Ediacaran fauna),<sup>38</sup> often having no close extant counterparts, this consideration takes on greater urgency.

### Multiple origins for structures that are unilaterally considered trace fossils

The fact that certain life traces are observed being formed in modern sedimentary environments is commonly overgeneralized as proof for the ichnofossil origin of *all* such structures in sedimentary rock. This overlooks the fact that the same or similar structure can have multiple origins. Clearly, the trace-fossil/body-fossil dichotomy is not an all-or-none proposition, even for members assigned to the same ichnogenus.

Let us focus on two ichnogenera: *Zoophycos* and *Paleodictyon*. The former is found on the modern ocean floor,<sup>39</sup> but this does not prevent some fossil *Zoophycos* from also being the body fossils of a certain type of sabellid worm.<sup>40</sup> Analogous reasoning applies to the reticular-network ichnogenus *Paleodictyon*. A computer simulation<sup>41</sup> shows that its origin can be reduced to the sophisticated movements of an elongate crustacean. On the other hand, a

deep-ocean polygonally-shaped xenophyophore (a type of giant protozoan) may be responsible for *Paleodictyon* (as either a trace fossil or body fossil).<sup>42</sup> Finally, at least some ‘stone honeycombs’ referred to the ichnogenus *Paleodictyon* are probably the body fossils of certain colonial algae.<sup>43</sup>

### Some biological candidates for rapid burrowing

There are numerous organisms whose potential for rapid burrowing is immediately relevant to Flood deposition, as long as they do not require clear water.<sup>44</sup> The foregoing considerations are doubtless facilitated by the fact that several different animals can usually make the same trace fossil or bioturbed horizon (figure 1).

The organisms most capable of disturbing the sediment during the time constraints inherent in rapid Flood deposition are those that can burrow through or across centimetres to tens of centimetres of sediment in a matter of seconds to minutes. There are many such organisms, and space limitations permit mention of only a few of them. Among annelid worms, such rates have been measured for *Sipunculus*,<sup>45</sup> *Ophiodromus*,<sup>46</sup> *Nephtys* and *Arenicola*.<sup>47</sup> Such rates hold for certain mollusks, including numerous kinds of bivalves,<sup>48–50</sup> certain razor clams,<sup>51</sup> the pelecypod *Neotrigonia*<sup>52</sup> and several different kinds of gastropods.<sup>53</sup> They also hold for many crustaceans, including the amphipod *Parahaustorius*,<sup>54</sup> the isopod *Tylos*<sup>55</sup> and various crabs.<sup>56–58</sup>

On the other hand, it is unclear if any trace fossils necessarily require long periods of time for their formation. *Cruziana* and *Rusophycus* can be formed by organisms within, at very most, 4–5 days.<sup>59</sup> Pointedly, the common trilobite self-burial trace *Rusophycus* may be analogous to traces produced by the modern crab *Emeritana*, which can completely conceal itself in sediment in a few seconds.<sup>60</sup> As noted earlier,<sup>37</sup> *Zoophycos* is no longer considered as a slowly-constructed ichnofossil. Furthermore, large and complex individual ichnofossils, including common ones such as *Cruziana*<sup>61</sup> and less common but metre-sized ones visually reminiscent of washboards,<sup>62</sup> can all form within strata.



**Figure 2.** Chondrites. This common ichnofossil resembles the branching burrows constructed by the modern bivalve *Thyasira*<sup>109</sup>, and may be related to the extraction of H<sub>2</sub>S from the sediment<sup>110</sup>. Scale: 1 cm. Ordovician (Cincinnatian), Ohio, USA.

Consequently, time is saved by the fact that sedimentation does not have to be interrupted as a prerequisite for their construction, and this assumes even greater significance in the light of the PPLC hypothesis developed below.

Extensive bioturbation of individual sedimentary layers can also be effected rapidly. Certain urchins can rework the upper 5 cm of sediment in 3 days.<sup>63</sup> Moreover, depending primarily upon the density of fast-burrowing organisms such as callianassid shrimp, a 12-cm thick layer of sediment can be 67% bioturbated (ichnofabric index of ~5, figure 1) in as little as 15.5 hours:

‘Of course, these values provide only the loosest constraints upon the duration of the burrowing interval for this bed. However, it is clear that extensively bioturbated horizons do not necessarily require protracted intervals of time for their development.’<sup>64</sup>

To the extent that the above-quoted rates are realistic and widely applicable, it is clear that extensively-bioturbed horizons themselves pose no problem to the time constraints of a one-year Flood.

### **Beyond uniformitarianism: rethinking ichnofossil construction**

As with everything else in geology, trace fossils have been viewed exclusively through a lens of uniformitarianism, resulting in a narrow actualistic interpretation for their origins. Ichnofossils have been narrowly conceptualized as the products of organisms living on ancient seafloors comparable to the seafloors found on Earth today.<sup>65</sup> This framework for thinking is not required as I will show by focusing on potential and actual limiting factors imposed on organisms by their transportation, the oxygenation of sediments, and the immobilizing effects of thick sediment overburden. Owing to the magnitude of its relevance to catastrophic Flood deposition, an entire section is devoted to the latter.

Very little research has been conducted on the burrowing behaviour of organisms that have undergone transport and then been buried by massive catastrophic sedimentation, as must have typified the Flood. One notable exception is the study of ‘doomed pioneers’.<sup>66,67</sup> According to this concept, it is believed that organisms washed downslope onto an inhospitable seafloor surface can sometimes burrow for a short time before they die. Of especial relevance to Flood geology is the fact that numerous types of marine life are known to be capable of surviving transport, after which many of them will commence burrowing when deposited on or within a layer of sediment.<sup>68</sup> Also, it is acknowledged that ichnofossils resulting from transported organisms have often gone unrecognized in the fossil record owing to difficulties in their recognition.<sup>69</sup>

The survival of burrowing organisms is, under present conditions, limited primarily by the availability of oxygen,<sup>70</sup> either at the sediment-water interface or to whatever depth to which the sediment is oxygenated.<sup>71</sup> Under the

low depositional rates that typify modern sedimentary environments, oxygen becomes depleted long before it can be replenished with fresh oxygenated sediment, and the seafloor sediments usually become anoxic at shallow depths. During the Flood, by contrast, oxygen is less likely to have been the main governing factor. Large-scale mixing of water and sediment facilitated the accumulation of great thicknesses of sediment complete with entrapped oxygen. In time, bacteria would use up the oxygen. However, modern experience suggests that this does not happen immediately. For instance, a pulse of oxygenated sediment delivered into a dysaerobic environment can maintain much of its oxygenation for over a month.<sup>72</sup>

So long as other factors did not become limiting, organisms could survive and burrow until the entrapped oxygen was exhausted. Pointedly, the depletion of oxygen in the sediments does not *ipso facto* mean the end of bioturbation. Certain marine animals can not only survive but also continue disturbing the surrounding sediment for days or weeks after the onset of hypoxic conditions, especially if they happen to be adapted to dysaerobic environments.<sup>71</sup>

### **Burrowing limited by the immobilizing action of sediment overburden**

Under actualistic conditions, the effects of a sudden sedimentary cover are relatively unimportant to the overall burrowing behaviours of marine organisms. While ‘catastrophic’ seafloor sedimentation can deposit a few tens of centimetres (occasionally more) within a few hours, the amount deposited in a single ‘catastrophe’ (e.g. a storm) is usually much less. Moreover, little or no sediment is raining down on the seafloor most of the time. Consequently, sudden sedimentation has only a local and temporary effect on overall bioturbation<sup>73</sup> in nearshore and offshore environments. In striking contrast, owing to the geographically-widespread and sustained metres-per-hour sedimentation rates characteristic of the Noachian Deluge, the immobilizing action imposed by thick sediment upon buried organisms must have been the primary factor limiting prolonged burrowing into the sediment encasing them.<sup>74</sup> The immobilizing action derives from a pressure-induced compactional stiffening of the sediment surrounding the organism to the point that it cannot move, possibly including the direct squeezing of the organism itself.

Measured on a generalized scale that extends to great depths, lithostatic pressure of sediments increases at a rate of 23 kPa/m.<sup>75</sup> However, a number of local factors, singly or in combination, were likely important in the alleviation of the immobilizing effects acting upon organisms that were suddenly buried by considerable thicknesses of sediment. These include organisms that were:

1. Inherently difficult to immobilize or crush,
2. Fortunate to be entombed within lenses of relatively uncompacted sediment,

3. Situated in sediment that behaved as an elastic solid, leading to cracking during burrowing,
4. Buoyed within water-supported debris flows, and
5. Situated in sediment sandwiched between *Penecontemporaneous Partially Lithified Crusts* (PPLCs).

**Each is considered in turn.**

1. The inherent difficulty to immobilize or crush.

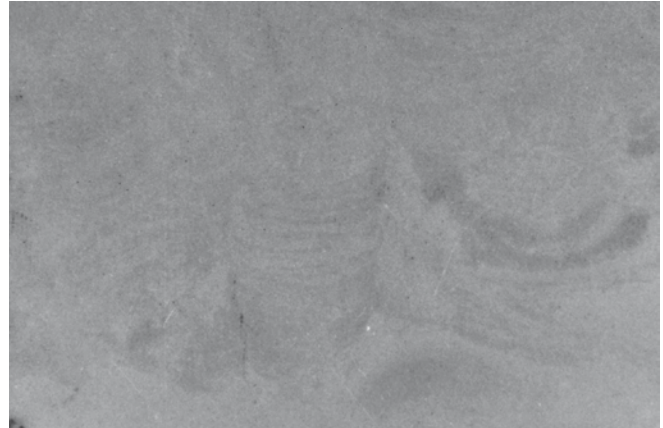
This is difficult to evaluate as no systematic experiments have, to my knowledge, ever been conducted on the upper limits of mobility among very deeply-buried organisms in different kinds of sediment. A classic experimental study<sup>76</sup> on burrowing bivalves indicates virtually complete immobilization under an overburden of less than one metre. However, this finding must be tempered by the fact that sand is, unlike most other sediments, very permeable and thereby rapidly dewatered and compacted,<sup>77</sup> leading to a very effective stiffening of the material under relatively low overpressures. Anyone who has had one's limbs recreationally buried by beach sand can attest to this.

Some aquatic invertebrates can burrow two or more metres below the sediment-water interface.<sup>78-80</sup> While this is obviously not the same as having a comparable thickness of sediment suddenly deposited upon them, it does indicate an ability to deal with a significant amount of sediment compaction. It should be added that a variety of marine animals expel water in order to fluidize the sediment around them to facilitate movement and/or burrowing.<sup>81,82</sup> This fluidization of sediment immediately around the organisms may alleviate the effects of compaction, creating 'wobble room' for potential protracted post-burial burrowing.<sup>83</sup> Finally, there is a series of enigmatic ichnofossils which, if correctly interpreted as escape burrows, indicate that some organisms can burrow through a staggering eight metres of sediment,<sup>84</sup> at least under some circumstances.

2. Fortunate entombment within lenses of relatively uncompacted sediment.

Very rapid deposition commonly produces loose packing of sediment, as exemplified by certain avalanche deposits, which can be either subaerial or subaqueous.<sup>85</sup> In addition, under conditions of rapid deposition, local inhomogeneities in the packing of the sedimentary particles occur frequently. Consequently, lenses or pockets of relatively uncompressed sediment, surrounded by much stiffer, strongly-packed sediment, may well have existed during Flood deposition.<sup>86</sup> Organisms situated within such lenses may have been spared from immobilization for significant amounts of time, allowing for persistent burrowing of multiple horizons even within thick layers of sediment.<sup>87</sup>

3. Situated in sediment behaving as an elastic solid, leading to cracking during burrowing.



**Figure 3.** A conical burrow, near centre of picture, containing spreite structures (upward-curved superimposed discs of sediment pushed by a burrowing marine animal), resembling *Teichichnus*.<sup>111</sup> Maximum width of cone approx. 5 mm. Silurian Racine Formation, Chicago area, USA.

It has recently been discovered that sediment can behave as an elastic solid that is susceptible to cracking by organisms that attempt to burrow through it.<sup>88</sup> This reduces the energy expenditure of burrowing. What is unclear, however, is whether the creation of local cracks around the organism would play any role in the alleviation of the immobilizing effects of thick overburdens of sediment. Again, experimentation is needed.

***Prolonged multiple-horizon burrowing within thick slurry flows?***

4. Buoyed within water-supported debris flows.

Thick debris flows<sup>89</sup> and sedimentary gravity flows<sup>90</sup> (as occur in high-density turbidity currents) can support large (even boulder size) objects through the buoyant action of the interstitial water. Even the individual sedimentary grains are able to float. One specialist in trace fossils suggested that displaced marine invertebrates could burrow within such slurry deposits.<sup>91</sup> If so, then more than one bioturbated horizon could be constructed at a time as long as the watery state of the sediments protected burrowing animals from immobilization.

But how common are slurry deposits in the Phanerozoic sedimentary record? Again, no clear answer is forthcoming in the conventional uniformitarian literature. It is interesting to note that 'mantle and swirl' biogenic structures, characteristic of soupy sediments, have probably been widely misidentified or misinterpreted in previous studies.<sup>92</sup> However, the recognition of onetime slurry deposits may not be straightforward. For example, depending upon various local conditions, sediments once deposited while in a water-rich state may or may not show such things as size grading or water-escape structures.<sup>93</sup>

### PPLC: the Penecontemporaneous Partially Lithified Crust Hypothesis

#### 5. Situated in sediment sandwiched between Penecontemporaneous Partially Lithified Crusts (PPLCs).

By way of introduction, a heavy overburden does not necessarily imply immobilization or severe overpressure acting on whatever lies underneath it. In architecture, the arch serves to bear and disperse the weight of the material above it, thereby protecting whatever lies beneath it. The same principle is potentially applicable to thick sedimentary sections, even though most sedimentary layers are flat. As a consequence of the Flood, one must factor not only very rapid deposition, but also very rapid penecontemporaneous cementation, which furthermore may have affected certain horizons of sediment before others. This may have led to the temporary situation of lithified crusts interspersed with sediment that needed much more time to undergo lithification.

Depending upon their resistance to deformation, some of these lithified crusts (PPLCs) may have behaved like arches to varying degrees. Organisms that happened to be entombed in the cone-shaped volume of sediment underneath the PPLCs were temporarily protected against the immobilizing action of the overlying column of sediments,<sup>94</sup> allowing them to build burrows or even more sophisticated trace fossils (figure 4, right side). They could continue doing so until one of the following conditions was reached, causing their deaths:

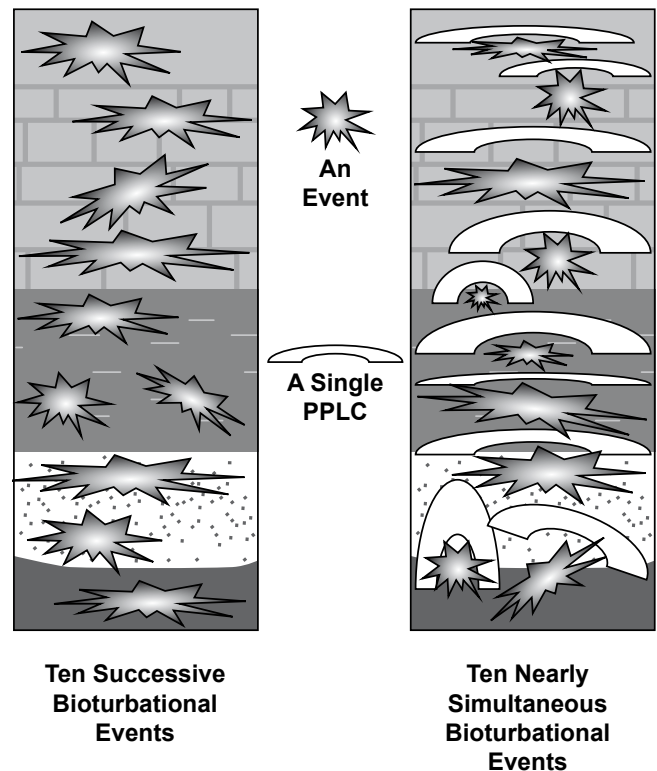
- The life-supporting substances in the sediments became exhausted,
- The overlying Flood-deposited sediment became so thick that the PPLCs could no longer deflect the overpressure that produces severe compactional stiffening of sediment (or direct injury to the organism),
- The penecontemporaneous lithification of the PPLCs had spread to the horizons of sediment containing the burrowing organisms. In time, the lithification would encompass most if not all of the local sedimentary column. Consequently, onetime PPLCs would not usually be independently identifiable to the modern field geologist.

As a consequence of PPLCs, burrowing organisms' activities were not restricted to the one-horizon-at-a-time bioturbation of sediment at or near the sediment-water interface where the immobilizing action of overlying sediment is slight to nonexistent (figure 4, left side). Instead, a series of superposed burrowing organisms could simultaneously rework the sediment (figure 4, right side), thereby eliminating a considerable amount of time supposedly necessary for the collective biological processing of Phanerozoic sediment.

Let us touch on a few of the petrographic details of the generation of PPLCs themselves. Carbonate minerals are one of the most common cementing agents acting on sediments. Early precipitated cement formed at or not far

below the depositional interface will increase the bearing strength of the sediment.<sup>95</sup> Let us now apply this to the formation of PPLCs. There are several types of mechanisms known for the rapid induration of carbonates, and many of these may shed light on the genesis of individual PPLCs. The first is beachrock formation, which is facilitated by the CO<sub>2</sub> degassing responsible for the formation of calcite crusts, and is capable of indurating sediment in a matter of hours.<sup>96</sup> The repeated percolation of meteoric and marine water is believed important for rapid beachrock formation,<sup>97</sup> and one can envision comparable processes occurring during the Flood on much larger scales. In other contexts, the mechanical agitation of saturated water (obviously relevant to Flood conditions) can also precipitate a layer of carbonate in a matter of hours.<sup>98</sup>

Travertine precipitation, facilitated by large releases of CO<sub>2</sub> bubbles, can occur at the water-air interface in a matter of minutes,<sup>99</sup> creating a surface scum of CaCO<sub>3</sub> precipitate. Occurring on a vastly larger scale during the Flood, thick floating carpets of CaCO<sub>3</sub> precipitate, once stranded by ebbing floodwater, could rapidly indurate and form individual PPLCs. These examples hardly exhaust the potential for rapid carbonate lithification during the Flood, as the relevant processes are still not well understood, even in actualistic contexts.<sup>100</sup>



**Figure 4.** The PPLC hypothesis. In contrast to the time-consuming one-horizon-at-a-time bioturbation posited by conventional uniformitarian thinking (left), several horizons are bioturbed simultaneously (right). This can happen thanks to the fact that PPLCs (idealized as arches in this figure) temporarily protect the deeply-buried marine organisms from the immobilizing action of thick overlying sediment.

## Flood action and overall bioturbation in Phanerozoic sedimentary rocks

The foregoing can be summarized into a unified diluvial setting, considering first those stratigraphic sections where bioturbation is sporadic, and then focusing on thick sections that are extensively bioturbated. To understand bioturbation in general during the Flood, one must first consider the frequency of each ichnofabric index for Phanerozoic sedimentary rocks in general. As illustrated in figure 1, the ichnofabric index is a semiquantitative measure of the degree of disturbance of sediment by bioturbation. The author knows of no comprehensive study addressing the relative frequency of given bioturbation indices in Phanerozoic rock as a whole. Personal field experiences suggest that sedimentary layers having little or no bioturbation are the general rule. In addition, thick geosynclinal sediments, whose very thickness of superposed bioturbated horizons should impose the greatest time challenge to Flood geology, are conspicuous in having large sections (hundreds of metres or more) devoid of trace fossils.<sup>101,102</sup>

Let us first consider burrowing for which enough time was available locally during the Flood for the bioturbation to take place one horizon at a time. This situation is manifested as horizons of bioturbated sediment, usually with low ichnofabric indices (figure 1), often alternating with layers having no bioturbation. In this scenario, each pulse of floodwater deposited only a relatively thin mantle of oxygenated sediment at a time, with some layers of sediment having enough time to undergo a brief period of bioturbation before the next pulse of floodwater deposited more sediment and, in accordance with conventional thinking, immobilized the previously-deposited burrowers. Under the assumption of extremely episodic conditions as an upper limit, sufficient time was available for the construction of up to thousands (or more) of such superposed bioturbated horizons.<sup>103</sup>

Very thick sedimentary lithologies that have been extensively bioturbated present more of a challenge to a Flood model, even if they occur at or near the top of the local lithostratigraphic column. Thick sequences of sedimentary rock, characterized by high ichnofabric indices, and occurring in undoubted superposition, may have had insufficient time during the Flood for them to be explained by one-horizon-at-a-time bioturbation. One must then contemplate the bioturbation of appreciable thicknesses of sediment, the multiple horizons of which are being bioturbated at the same time, through the application of the mechanisms discussed previously (lenses of 'fluffy' sediment, slurry flow conditions, and the PPLC hypothesis).

Let us now consider an example of extensive thicknesses of bioturbated sediment. Attention is directed to the ichnofabric indices comprising 48 Cambrian stratigraphic sections and 1,151 total metres of sedimentary strata in the western USA,<sup>104</sup> which also includes some Ordovician strata.<sup>105</sup> Only a small fraction of the total thickness has an ichnofabric index of 1, while the majority of the total thickness has an ichnofabric index of 3 or greater. However, the foregoing ichnofabric

analyses utilize an averaging of beds, not a bed-by-bed inventory of ichnofabric. Consequently, many non-bioturbated beds may be lost within the coarse resolution inherent to the analyses. Second, one must ask how many of the bioturbated horizons are truly superimposed. This question should be considered in terms of both the lateral continuity of bioturbated horizons and their frequency and bioturbational intensities in vertical stratigraphic sections. In terms of the former, one study<sup>106</sup> shows that ichnofabric indices can be traced horizontally for 200 m in some instances, but much less in others. To the extent that highly-bioturbated horizons are generally discontinuous, the abundance of considerable thicknesses of highly-bioturbated sedimentary rock may be at least partly illusory. Seemingly continuous highly-bioturbated beds may actually contain considerable numbers of thin, discontinuous, intercalated nonbioturbated layers, most of which are not noticed because they are not cut by the same outcrop face or borehole.

However, it must be stressed that even thick seams of continuously highly-bioturbated sediments are fully compatible with the PPLC hypothesis, although not operating to the same degree of mutual contemporaneity as depicted in figure 4, right. Pointedly, the PPLC layers themselves can be highly bioturbated. For example, consider the following series of events: A pulse of sedimentation takes place and, as is customary, experiences more rapid and extensive bioturbation at the sediment-water interface than deeper within the layer. Soon thereafter, the upper layer lithifies, arresting the bioturbation and forming a PPLC. The much-slower bioturbation taking place within the lower part of the layer can now continue for some time, thoroughly mixing the lower layer all the while the newly-formed PPLC protects it from the overpressure imposed by a successive pulse of deposited sediment. The latter, in turn, experiences its own bioturbation and PPLC formation. The end result is a thick but cryptically composite, highly bioturbated interval of sediment.

## Conclusion

An unknown and potentially large fraction of individual ichnofossils may be misidentified organic features or body fossils. A 'Certainty Index' should be developed to rate trace fossils, on a case-by-case basis, as to the perceived certainty of their ichnofossil origins.

A large and diverse series of burrowers are known to be capable of disturbing sediment in a matter of seconds to minutes, and entire beds can be overturned in less than a day. However, much more must be known about trace fossils made under non-actualistic conditions before a comprehensive picture can emerge of their construction during the Flood. In particular, knowledge, currently very sparse, on the behaviour of organisms transported *en masse* and then suddenly encased by thick sediments, needs to be gained. It is also necessary to experimentally determine the length of time that suddenly-buried organisms can continue burrowing while situated in pockets of uncompressed sediment, and to what extent these pockets can remain meaningfully uncompressed in the face of

rapidly-increasing overburden. More information is needed about soupy sediment in terms of organisms' prolonged ability to burrow in it, and for its ability to retain its soupy condition without later giving evidence of ever having been in that state.

The efficacy of the PPLC hypothesis requires experimental validation. One such would be determination of the extent to which a promptly-lithified crust is capable of deflecting the overpressures of overburden to the point of allowing organisms trapped below it to burrow for significant amounts of time.

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